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CALCULATED RESPONSE OF AIR-WALL DOSIMETERS OR GEIGER-MUELLER TUBES TO MONOENERGETIC PHOTONS BETWEEN 1 AND 10 MeV

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ABSTRACT

The question of registering dose from weapon and reactor photons of 2 to 10 MeV energy has led to a study of the capability of conventional dosimeters and Geiger-Mueller tubes to respond accurately to these energies. Calculations of the response of thin and thick air-wall dosimeters have been made. The results are given as "efficiencies", or the ratio of the chamber response in charge per cubic centimeter in the dosimeter per incident photon fluence, to the same quantity in an ideal air wall chamber in electronic equilibrium. Stated in this way the results do not specifically refer to any type of chamber, but rather to interactions which result from normally incident photons. A very broad beam including scattered photons or an isotropic photon flux should give results approximately proportional to those computed.

The cases are analyzed of 1/16-in. and 1/8-in. air wall dosimeters under bombardment with these high energy photons, and also under bombardment with these photons plus the electron flux density coming from an air absorber of sufficient thickness to ensure primary to secondary radiation equilibrium. Finally dosimeters of two different wall thicknesses, 2.5 and 5 grams/cm^2, are studied, the latter of which can reach primary-to-secondary equilibrium under 10 MeV photons (and, of course, under all lower energies). The attenuation of the primary flux density is relatively small even at the larger thickness.

The results given in tables and a graph show that the thin wall dosimeters will give a distorted indication of dose at higher energies. The chamber with 5 grams per square centimeter wall responds in constant ratio to the response of the ideal air wall chamber for photons from 1 to 10 MeV and can therefore be used under all conditions for a register of dose.

SUMMARY

The Problem

To determine the capability of personnel dosimeters to respond to gamma radiation from weapons and reactors to 10 MeV.

The Findings

Conventional thin walled dosimeters would give an error in dose estimate for gamma energies above 2 MeV several times greater than present tolerances. An air-wall dosimeter 5 grams per square centimeter thick would give a nearly uniform response to dose from gamma photons to 10 MeV.

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INTRODUCTION

The possibility of nuclear attack on Naval vessels or installations, and exposures around nuclear reactors, raises the question of the capability of available personnel dosimeters and Geiger-Mueller tubes to respond to high energy radiation dose, within practical limits of accuracy, for both tactical and administrative purposes.

The calculations given below aim at estimating the maximum response from an element of chamber wall of given thickness from interacting with a normally incident gamma photon having a probability of producing a high energy electron. The emerging electron is assumed to enter a cavity from which the charge per unit volume from unit photon fluence could be collected. The response is a maximum for this specialized direction of the photon with respect to the wall; in contrast a beam of photons striking cylindrical walls would give a progressively decreasing response as the angle with the normal increased.

As a means of characterizing the response, the ratio of the charge per cubic centimeter of cavity from a photon per square centimeter is compared to the same quantity from photons striking an ideal air-wall chamber in primary-to-secondary radiation equilibrium. This ratio, called the efficiency of the particular wall thickness to photons in the energy range from 1 to 10 MeV, is a measure of the effectiveness of the wall thickness in producing ionization in the cavity and hence leading to an indication of dose. It can also be looked at as the ratio of the charge per centimeter per incident photon in the assumed and the ideal chamber.

It will be seen that the calculated response of thin-walled dosimeters to high energy photons is relatively low and decreases with rising photon energy. The failure to respond uniformly to dose over the energy range will appear to be due to failure to reach primary-to-secondary radiation equilibrium in the thin wall. A 5 grams/cm^2 wall, however, gives air-proportional response to 10 MeV. A graphical comparison is made of the thin and thick wall dosimeter responses.

If the responses calculated were applied to an assumed spectrum of high energy gamma photons, the maximum response of a chamber of the given wall thickness to normally incident photons could be computed. The actual response of a dosimeter of any given electrode geometry

could be computed on a machine after (a difficult) analysis of the effect of the particular geometry on the responses of each element of wall to the photons. Both these developments however are much later steps in response computations than are attempted here. Considering the distribution of these higher energy photons in an isotropic flux the response of any given chamber might be expected to be proportional to the responses computed here for the photons of any given energy. The proportionality factor would certainly be less than unity.

Calculations of Response

In the simplest case, an air-wall dosimeter element of 1/16 in. wall thickness is assumed bombarded with unit photon fluence over this range. At these higher energies the wall thickness is only a fraction of the range of the secondary electrons, and transmission of secondary electrons is above 90 percent. The secondary electrons move principally in the forward direction through the wall into the region from which the ions can be collected. Each electron then produces ions along its track at or near minimum ionization, from which figure the charge per cubic centimeter per incident photon fluence can be computed. The same quantity is computed for an equilibrium, ideal, air-wall region, namely, charge per cubic centimeter per unit photon fluence from that flux density of photons of different energy which give an electrostatic unit of charge per hour per cubic centimeter of standard air. The ratio of these two quantities, in the assumed and the ideal cases, for photons at any energy, gives the efficiency of the assumed detector with photons normally incident; and is approximately proportional to the detector response under an isotropic flux of photons.

Such response computations apply also to the air wall GM tube with filter, for normally incident photons. The two cases, when effective wall thicknesses are equal, are the same, since both operate on ions passing through the gas space, although the specific ionization and event rate in the GM tube are different. The filter determines the number of electrons penetrating the walls. If the tube is effectively air-wall, of suitable thickness less than the electron range, the responses should be proportional since the GM tube should be calibrated by reference to an air-wall dose-reading chamber.

In the cases considered the intention is to show the relative responses for different energy photons, so that attention should be

directed mainly to this comparison; the intercomparisons between assumed dosimeter wall thicknesses lead to the idea of making a uniformly sensitive chamber to all photon energies considered.

To compute the actual response of a tube with cylindrical geometry it would be necessary to compute transmission of electrons through the variable thicknesses presented to a beam by the round walls, with consequent absorption and loss of secondary electrons, over all but the central (plane wall) section of the tube. As was mentioned, under an isotropic flux the effects of geometrical shape would be minimized, and the results should be proportional to the approximation computed here.

As will be seen, the difficulty in registering response proportional to intensity or flux density over the range of energies above 2 MeV in comparatively thin-wall conventional dosimeters is that radiation equilibrium is not reached in the wall. That is, the ratio of secondary to primary intensity beyond a certain thickness, approximately equal to the range of the secondary radiation (electrons) cannot reach the maximum in the small thickness of absorber available in the walls. Hence the walls as electron radiators to the dosimeter cavities give only a fraction of the equilibrium secondary radiation, different for each energy, which then travels through the cavity with the remaining, unabsorbed, fraction of the original photon flux density.

The case mentioned above, namely that of the 1/16-in. wall chamber does not assume that primary to secondary equilibrium has been reached in the air between the source and the thin walled dosimeter. Since the range of a 10 MeV electron is about 40 meters in air, incident weapon radiation would be in equilibrium, where reactor radiation would not. Another calculation is therefore made for the 1/16-in. wall (and also 1/8-in. wall) in which it is assumed that a flux of secondary electrons in equilibrium with the primary radiation is also striking the dosimeter and increasing the registered dose.

It will be seen that the increase in response is appreciable from the secondary electrons at the higher energy. Nevertheless the efficiency is not constant with energy so that a dosimeter would not register the correct dose in general because of the different weighting in the dosimeters, depending on energy, wall thickness and source distance.

Because of the failure of the thin-walled dosimeter to register dose proportional to that of an ideal airwall chamber it is necessary to consider a more general case. The assumption is therefore made that

a dosimeter with air walls 5 grams/cm^2 thick is subjected to unit fluence of these energetic photons. (Such a dosimeter might be the monitor for a group of persons subjected to high energy radiation). This dosimeter would allow radiation equilibrium with 10 MeV photons, since 5 grams/cm^2 is approximately the range of 10 MeV electrons. It would also evidently be in equilibrium with all lower energy photons, although the intensity of the lower energy photon beam would be somewhat attenuated by absorption. The electrons reaching the cavity from such a radiation would be only those coming from a thickness in the wall next to the cavity equal to the range of the particular energy of electron. Thus this dosimeter, with absorbing shield, would give the maximum equilibrium response available at this highest energy, 10 MeV, for any air-wall dosimeter of this or greater thickness.

Response of an intermediate thickness of 2.5 grams/square centimeter was computed to see if the larger thickness was necessary to get constant efficiency over the entire range of energy.

The formulas developed for the thick walled dosimeters, and for that considering equilibrium established in air mentioned above require knowledge of the secondary absorption coefficient; that is, for electrons of energy above 2 MeV. No actual coefficient is known but an assumption leading to such a coefficient based on electron range is discussed in an appendix, and the essential correctness of the coefficient computed is shown (Table 7 in Appendix).

It will be seen that the response of the thicker-walled chamber is approximately energy independent over the photon energy range from 1 to 10 MeV and therefore weights ionization, and hence dose, correctly over this range.

Computations

a. Ideal Air-Wall Chambers

The first quantity computed is the number of Coulombs of charge liberated per cubic centimeter in air per incident photon fluence in an ideal air-wall chamber. Data over the range of photon energies from 1 to 10 MeV are taken from (Ref. 2), which gives a graph taken from another reference APEX 176, page 113, showing the gamma flux densities corresponding to 1 roentgen per hour over this range of energies.

TABLE 1

Charge per cubic centimeter per incident photon fluence

Photon energy, MeV	1	2	3	4	5	6	7	8	9	10
Flux density of photons 10^5 units	5.5	3.2	2.4	1.9	1.7	1.5	1.3	1.2	1.1	1.0
Coulombs per cm^3 per photon/cm^2 10^{-19} units	1.7	2.9	3.9	4.9	5.5	6.2	7.0	7.7	8.5	9.2

(Specific current at 1 r/hr 0.926×10^{-13} amps/cm^3)

b. Thin Air-Wall Chambers

In order to compute the charge per cubic centimeter per photon fluence, or the response, when a beam of gamma photons interacts with a thin air wall, it is necessary to know the extent of interaction of the beam. The interaction is given by the change in intensity of primary photons across the absorber thickness. Each primary photon absorbed in a Compton process is assumed to yield an electron which emerges from the wall and goes into the cavity, ionizing at a rate depending on its energy. A similar process is assumed to give ionization from pairs of electrons and positrons entering the cavity having equal energies (E-1)/2 MeV, where E is the primary photon energy.

The charge per cubic centimeter per unit photon fluence can be looked at, for brevity, as the number of coulombs per cm of track per incident photon.

Then for initial intensity $I_1(E)$ at photon energy E the number of charges per centimeter of track in the cavity per incident photon is:

$$\bar{q}c = \mu_{ac}\Delta x \frac{45}{[\beta(F)]^2} e \qquad \frac{\text{coulombs}}{\text{cm-photon}} \qquad \text{(I)}$$

The first two factors, $\mu_{ac}\Delta x$ give the number of photons materializing as charges in the walls and penetrating into the cavity, from the thin target approximation, where Δx is appreciably less than the range of the secondary particle, and $dI_1/I_1 = \mu_{ac}\Delta x$. The transformation to fraction of photons interacting by attenuation of intensity results from the relation:

$$\frac{d\,I_1/E}{I_1/E} = \frac{dF}{F}$$

where E is the initial photon energy, and F the photon flux density. Hence the two factors give the number of electrons entering the cavity per initial photon, to a first approximation. The Compton electron's ionization density is then taken at the photon energy, at the rate $45/\beta(E)^2$ per centimeter of air where β is the ratio of electron velocity to that of light (Ref 3). The symbol e stands for the electron charge in coulombs, to convert the charges resulting to coulombs per cubic centimeter.

The next contribution to dosimeter response results from recognizing that each pair produced gives two ionizing particles entering the cavity, because of the predominantly forward transfer of momentum to the pair. This number of electrons and positrons per photon is computed by a formula similar to (I) using the pair absorption coefficients μ_{ak} in air. The pair energy is taken at one-half the photon energy minus the creation energy, 1/2(E-1), and the ionization rate at $2 \times 45/\left[\beta\frac{(E-1)}{2}\right]^2$. The resulting formula is then:

$$\bar{q}_{ak} = \mu_{ak}\Delta x \frac{90}{\left[\beta\frac{(E-1)}{2}\right]^2} e \qquad \frac{\text{coulombs}}{\text{cm-photon}} \qquad \text{(II)}$$

The approximation thus reached may be high; it is unlikely that it is low. The reason is that some of the electrons may not enter the cavity as assumed, particularly below 3 MeV, because of the internal energy loss in the wall, and the fact of the distribution over the forward direction. This may reduce the average electron flux density in the cavity but somewhat compensatingly increases the factor $45/[\beta(E)]^2$.

The charge per centimeter of track per incident photon tabulated below for the wall thickness, 1/16 inch, is compared in the following table with the same kind of quantity in air listed in Table 1 to get the efficiency of the dosimeter to detect dose at these higher energies.

(Background data and details of the computation: $\mu 1 = 10^3 \times (\mu_{ac}+\mu_{ak})$ for air wall density 1.20 grams/cm^3. $\Delta x = 0.158$ cm. Energy loss per milligram/cm^2 = 2 kev. Electron energy loss in 0.158 cm straight through traverse of wall is 0.38 MeV).

The fourth line from the bottom of Table 2 shows that the efficiency of the dosimeter in registering dose above 2 MeV is very small, owing to the failure to reach primary to secondary equilibrium in the thin wall. For double this thickness, or 1/8", the efficiency, second line from bottom, would be about double because of the greater number of primary photons interacted, although at low and intermediate energies a smaller fraction of the electrons materializing in the wall would emerge. Nevertheless the efficiency is still too low, and decreasing with energy, for a practical dosimeter. Its energy dependence is large and hence it would not weight ionization correctly as dose over the range of energy of interest.

Before taking up the case of the equilibrium thick-walled dosimeter it is desirable to compute the dose registered by a thin walled dosimeter under bombardment by an equilibrium mixture of electrons and photons, such as would come from a weapon, mentioned above. The doses registered are additive and nearly independent from these two fluxes, assuming only that unit photon density strikes the radiator to the dosimeter surface.

For the same thin walled dosimeter the relations giving the intensity of secondary electrons penetrating the dosimeter of an initial unit photon intensity at a distance equal to the range of the secondary electron are as follows:

$$I_2 = I_{20} e^{-\mu_2 t} \text{ (into cavity) and } I_{20} = \frac{\mu_1 I_{10}}{\mu_2'} \text{ (in equilibrium in air)}$$

where I_{20} is the secondary flux density at the dosimeter surface, μ_2 is the secondary absorption coefficient, cm^{-1}, in the dosimeter wall, t the dosimeter wall thickness, μ_1 the primary photon absorption coefficient in air, I_{10} the primary photon intensity entering the air absorber (radiator), and μ_2' the secondary absorption coefficient of air between the absorber and the source. I_2, then, in the cavity is given by:

$$\frac{I_2}{I_{10}} = \frac{\mu 1}{\mu 2 1} e^{-\mu_2 t} \quad \frac{\text{electrons into cavity}}{\text{photon on absorber air}} \qquad \text{(III)}$$

When μ_1 is broken into Compton and pair absorption coefficients, and the resulting secondary ions multiplied by the specific ionization as before, corresponding to the appropriate energies, computations give the following:

Table 2 Detection of thin air wall cavities for photon energies 1 to 10 MeV.

Photon energy, MeV Compton effect	1	2	3	4	5	6	7	8	9	10
μ_{ac} cm^{-1} 10^{-2} units	3.6	2.95	2.55	2.25	2.10	1.80	1.70	1.53	1.43	1.30
$\mu_{ac}^{\Delta x}$ 10^{-2} units	0.569	0.461	0.403	0.356	0.332	0.284	0.269	0.242	0.226	0.205
$45/[\rho(E)]^2$ $\frac{\text{electrons}}{\text{cm}}$	50.4	47.7	46.8	46.4	45.9	45	45	45	45	45
$\bar{q}c$ $\frac{\text{coul}}{\text{cm-photon}}$ 10^{-19} units	0.459	0.356	0.302	0.264	0.244	0.204	0.194	0.174	0.163	0.148
$\mu_{ac} = 10^3\ \mu$ for Compton absorption $\mu_{ac} = 10^3\ \mu$ for Pair formation										
Pair interaction										
μ_{ak} cm^{-1} 10^{-2} units	0.0	0.05	0.15	0.25	0.32	0.45	0.50	0.57	0.62	0.70
$\mu_{ak}^{\Delta x}$ 10^{-2} units	0.0	0.0079	0.0237	0.0395	0.0505	0.0711	0.0790	0.0900	0.0980	0.111
Pair energy MeV	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5
$90/[(E-1)]^2$		192	161	153	150	148	147	144	144	144
$\bar{q}k$ $\frac{\text{coul}}{\text{cm-photon}}$ 10^{-19} units		0.015	0.038	0.060	0.076	0.105	0.116	0.130	0.141	0.160
$\bar{q}_{accm\text{-}photon}$ $\frac{\text{coul}}{}$ 10^{-19} units	0.459	0.371	0.340	0.324	0.320	0.309	0.311	0.304	0.304	0.308
q_{air} $\frac{\text{coul}}{\text{cm-photon}}$ 10^{-19} units	1.70	2.92	3.9	4.9	5.5	6.2	7.0	7.7	8.5	9.2
Efficiency 1/16" wall	0.27	0.12	0.087	0.066	0.058	0.050	0.044	0.039	0.036	0.033
Normalized to 5 g/cm^2 wall	2.30	1.02	0.74	0.56	0.49	0.42	0.37	0.33	0.30	0.29
Approx. Effic. 1/8" wall	0.54	0.24	0.174	0.132	0.116	0.100	0.088	0.078	0.072	0.066
Normalized to 5 $gram/cm^2$ wall	4.50	2.04	1.48	1.12	0.98	0.84	0.74	0.66	0.60	0.58

The upper part of Table 3 shows the coefficients used in computing the dosimeter response from the Compton component of electrons using (III) and the appropriate ionization densities, with the corresponding efficiencies for 1/16" and 1/8" walls under the equilibrium electron flux density. The lower part of the table shows similar quantities for computing the response and efficiencies from pair interactions with photons in equilibrium with electrons.

The efficiencies from Table 3 are summarized in Table 4 for the two wall thicknesses under bombardment by an equilibrium flux of electrons from an air absorber. The total efficiency of each wall thickness is likewise given under bombardment by the electrons and also the photons incident on the thin air-wall dosimeter.

Considering first the response through the 1/16" wall, the efficiencies under the mixed flux show that the secondary electrons in equilibrium from the large air absorber add increasing fractions of the total efficiencies for increasing energies. Response to electron flux amounts to 75 percent of the total for secondaries from 10 MeV photons in the 1/16" wall and even 54 percent in the 1/8" wall.

Under the two bombardments the energy dependence is still marked, varying as much as a factor of 2 higher at 1 MeV. For the 1/8" wall, the total efficiencies under the mixed flux bring out the same energy dependence. Comparing the three lowest lines from each section of the Table shows that the thicker wall admits fewer electrons from the air absorber but gives more efficiency from the photon flux incident.

As with photons alone, considered above, in a tactical situation the responses of these two at high energy are too variable for use, because the weighting of the lower energy dose is excessive, where much of the flux will occur. The thin walled chambers are therefore also incorrect under mixed flux.

Five grams per square centimeter wall chambers

In order to obviate these dependencies, it is possible to use the thick wall air dosimeter mentioned earlier, namely that having an absorber of 5 grams per square centimeter thickness.

To compute an approximation to the response of such a dosimeter, the thick absorber relation for converting photon flux to electron flux must be used. It yields the number of electrons reaching the cavity (from within a range for the corresponding electrons) from photons of

TABLE 3

Charge per centimeter per photon in cavity from equilibrium secondary flux on thin wall cavities; and efficiencies

E_γ photon energy, MeV. From Compton recoil electrons	1	2	3	4	5	6	7	8	9	10
μ_a Compton cm^{-1} 10^{-5} units	3.60	2.95	2.55	2.25	2.10	1.80	1.70	1.53	1.43	1.30
μ_2 cm^{-1} (air) 10^{-2} units	1.29	0.648	0.432	0.324	0.259	0.216	0.185	0.162	0.144	0.129
μ_2 cm^{-1} (wall)	1.2	6.0	4.0	3.0	2.4	2.0	1.7	1.5	1.3	1.1
Coul/cm-photon 10^{-19} units	0.034	0.13	0.24	0.31	0.40	0.44	0.53	0.54	0.59	0.61
Effic. 1/16" wall	0.020	0.044	0.061	0.064	0.072	0.071	0.070	0.069	0.066	0.064
Effic. 1/8" wall	0.003	0.017	0.033	0.040	0.049	0.051	0.057	0.055	0.056	0.056
Electrons from pair interactions										
μak cm^{-1} 10^{-5} units		0.05	0.15	0.23	0.32	0.45	0.50	0.57	0.62	0.70
μ_2^1 cm^{-1} 10^{-5} units		2.58	1.29	0.86	0.65	0.52	0.43	0.37	0.32	0.29
μ_2 cm^{-1}		24.0	12.0	8.00	6.00	4.80	4.00	3.36	3.00	2.66
Coul/cm-photon 10^{-19} units	0	0	0.003	0.012	0.029	0.061	0.091	0.032	0.173	0.229
Effic. 1/16" wall (pairs)	0	0	0.00072	0.0024	0.0052	0.010	0.013	0.017	0.020	0.025
Effic. 1/8" wall (pairs)					0.002	0.005	0.007	0.010	0.013	0.016

TABLE 4

Total efficiencies from electrons and photons on 1/16" and 1/8" airwall dosimeters

Total efficiencies 1/16" wall, electrons from air, and photons on wall

Photon Energy, E, MeV	1	2	3	4	5	6	7	8	9	10
Effic. Compton Recoil electrons	0.0198	0.0436	0.0600	0.0640	0.072	0.071	0.074	0.070	0.069	0.066
Effic. pair interaction in equil.			0.0007	0.0024	0.0052	0.010	0.013	0.017	0.020	0.025
Total effic. electrons from air to wall	0.0198	0.0436	0.0607	0.0664	0.077	0.081	0.087	0.087	0.089	0.091
Effic. from photons on wall	0.23	0.116	0.078	0.060	0.052	0.046	0.040	0.036	0.033	0.030
Total effic. from electrons and photons	0.25	0.160	0.139	0.126	0.129	0.127	0.127	0.123	0.122	0.121

Total efficiencies 1/8" wall, electrons from air, and photons on wall.

	1	2	3	4	5	6	7	8	9	10
Effic. Compton recoil electrons	0.003	0.017	0.033	0.040	0.049	0.051	0.057	0.055	0.056	0.056
Eff. pair interactions in equil.					0.002	0.005	0.007	0.010	0.013	0.016
Total effic. from air electrons	0.003	0.017	0.033	0.040	0.051	0.056	0.064	0.065	0.069	0.072
Effic. from photons on wall	0.46	0.21	0.157	0.119	0.105	0.091	0.080	0.072	0.065	0.051
Total effic. from electrons and photons	0.46	0.23	0.19	0.16	0.16	0.15	0.144	0.137	0.134	0.133

the respective energies. When the number of electrons from Compton and pair forming interactions are added, as in the thin-walled case above, each at its energy and specific ionization, the charge per centimeter per incident photon is computed.

Because the wall thickness is expressed in grams per square centimeter it is convenient to use the appropriate mass absorption coefficients in the calculation. Consider an element of wall thickness at depth x grams per cm^2. The differential of secondary intensity which passes into the cavity from dx is approximately:

$$dI_2 = \mu_I \, I_x \, d\,x \, e^{-\mu_2(R-x)} \qquad \text{(IV)}$$

$\mu 1$ and μ_2 are the primary and secondary mass absorption coefficients.

When integrated over the distance from the front wall, zero, to R_{10}, the range of the 10 meV secondary radiation, the secondary intensity in the cavity is:

$$I_2 = \frac{\mu 1}{\mu_2 - \mu_1} \; I_{o1} \; (e^{-\mu_1 R_{10}} - e^{-\mu_2 R_{10}} \qquad \text{(V)}$$

μ_1 is tabulated, but μ_2 is not known.

An approximation for μ_2 (see Appendix) comes from the fact that no electron (secondary radiation) goes further through the wall material than the range of the secondary, so that in (V), above, the quantity $e\mu_2 R_{10}$ becomes zero and hence μ_2 is about $5/R$, which can be computed for each range and corresponding energy.

When the fast-electron flux density per unit photon, namely the ratio of I_2/E to I_{o1}/E, is computed for the flux density from the Compton and pair-forming interactions, as above, and each charge multiplied by the appropriate ionization density and charge per ion, e, there results the quantity, $\bar{q}$ coulombs per centimeter per photon as before.

$$\bar{q} = \frac{I_2}{I_{o1}} \frac{45}{[\beta(E)]^2} e = \frac{\mu_1}{\mu_2 - \mu_1} \left(e^{-\mu_1 R_{10}} - e^{-\mu_2 R_{10}}\right) \frac{45}{[\beta(E)]^2} \, e \, \frac{\text{coul.}}{\text{cm-photon}} \qquad \text{(VI)}$$

This quantity for the thick wall, 5 grams/cm^2 ionization chamber can then be compared to the corresponding quantity for the ideal free air ionization chamber to get the efficiency as in the tables above.

From the second and third lines from the bottom of Table 5, the photons of all energies are transmitted in nearly the same ratio, to this approximation. Looking only at the efficiencies in the third from the last line, for different energy photons, little variation with energy is seen. Hence the chamber response is proportional to that of the equilibrium air chamber, and therefore is energy independent. (The next to the last line gives the ratio of efficiencies at each energy to the average efficiency over the range, for the graphical comparison of all efficiencies discussed in Figure 1).

2.5 Grams/cm^2 Wall

Because of the possibility that a wall thickness equal to half the range might give a suitable weighted response, the response for the half-range thickness was computed. The second term in relation (V) is not quite negligible so it was necessary to substitute the assumed secondary coefficient of absorption for the fast electrons coming through the wall into the cavity. All quantities entering (V) are therefore given in Table 6.

The results show briefly that the efficiency, in the next to bottom line, is not constant to the highest energy, and decreases over the energy range.

DISCUSSION

This section brings together the results and conclusions of the several computations above, comparing the capabilities of the dosimeters in weapon and reactor photon fluxes. Figure 1 shows the efficiencies, normalized to the average efficiency of the 5 grams/cm^2 chamber. These include the efficiencies of a thin-walled chamber under photons alone (the non-equilibrium case) of two thin walled chambers under the photons plus thick-walled chambers under the photons plus equilibrium flux of electrons. Similarly the responses for both thick-walled chambers are shown, in both the equilibrium and near equilibrium (smaller) thickness.

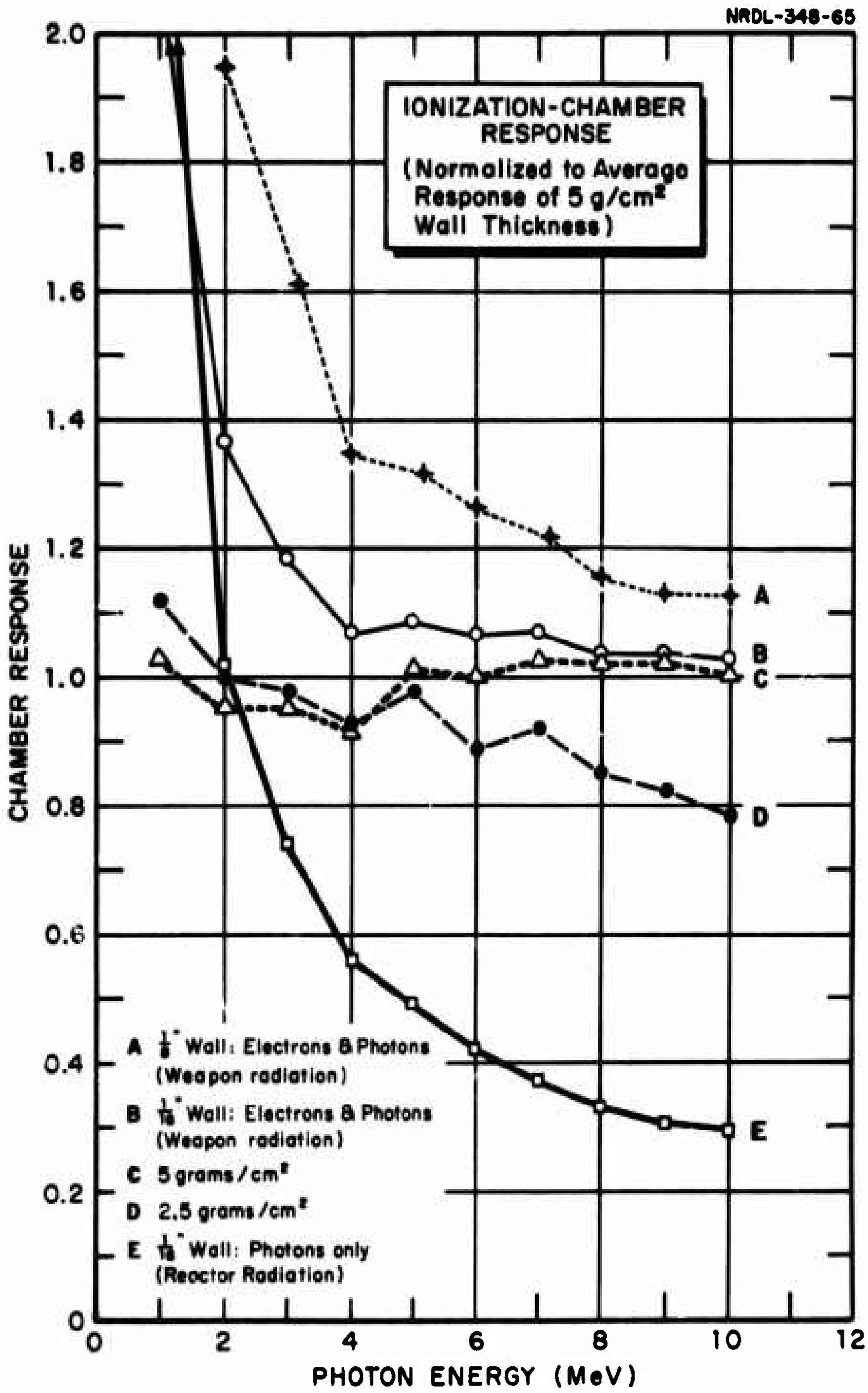

Fig. 1 - Ionization-Chamber Response (Normalized to Average Response of 5 grams/cm^2 Wall Thickness)

Table 5

Efficiency of 5 grams/cm^2 air-wall chamber for 1 to 10 MeV Photons.

Photon Energy, MeV	1	2	3	4	5	6	7	8	9	10
μ_{ac} cm^2/gram 10^{-2} units	3.0	2.45	2.12	1.87	1.75	1.50	1.42	1.27	1.19	1.08
μ_2 cm^2/gram	10	5.0	3.3	2.5	2.0	1.67	1.41	1.25	1.10	1.00
$\frac{\mu_{ac}}{\mu_2-\mu_{ac}}$ 10^{-2} units	0.30	0.49	0.64	0.75	0.88	0.89	1.00	1.02	1.08	1.08
$e^{-\mu_{ac} R_{10}}$ Reduced primary intensity at cavity.*	0.861	0.884	0.900	0.910	0.916	0.928	0.931	0.937	0.942	0.947
$\frac{\text{Coul.}}{\text{cm-photon}}$ 10^{-19} units	0.208	0.324	0.423	0.491	0.580	0.595	0.670	0.688	0.732	0.736
Pair Interactions μ_{ak} $\frac{\text{cm}^2}{\text{gram}}$ 10^{-2} units	0	0.042	0.12	0.21	0.27	0.38	0.42	0.48	0.52	0.58
μ_2 cm^2/gram	-	20	10	7	5	4.1	3.3	2.9	2.5	2.3
$\frac{\mu_{ak}}{\mu_2-\mu_{ak}}$ 10^{-2} units	-	0.0021	0.012	0.030	0.054	0.093	0.127	0.166	0.208	0.252
$e^{-\mu_{ak} R_{10}}$ Reduced primary intensity at cavity.*	1.0	1.00	1.00	0.990	0.986	0.980	0.980	0.976	0.974	0.970
Coul./cm-photon 10^{-19} units	-	0.004	0.016	0.046	0.079	0.135	0.182	0.233	0.292	0.351
Total coul/cm-photon 10^{-19} units from Compton pair inter.	0.208	0.328	0.439	0.537	0.659	0.730	0.852	1.921	1.024	1.087
Coul/cm-photon in air 10^{-19} units	1.70	2.92	3.90	4.90	5.5	6.2	7.0	7.7	8.5	9.2
Effic. of $5\frac{\text{grams}}{\text{cm}^2}$ wall (avge. 0.118)	0.122	0.112	0.112	0.109	0.119	0.118	0.122	0.120	0.120	0.118
Normalized to avge. 0.118	1.03	0.95	0.95	0.92	1.01	1.00	1.03	1.02	1.02	1.00
*From each interaction separately. Reduced primary intensity at cavity from both interactions.	0.861	0.884	0.900	0.90	0.90	0.91	0.91	0.92	0.91	0.92

Table 6

Response of 2.5 g/cm^2 air-wall dosimeter to high energy photons, and efficiencies.

Photon Energy, MeV	1	2	3	4	5	6	7	8	9	10
$e^{-\mu_{ac} \frac{R_{10}}{2}}$ (Compton)	0.93	0.94	0.95	0.96	0.96	0.96	0.97	0.97	0.97	0.98
$e^{-\mu_{ak} \frac{R_{10}}{2}}$ (Pair)	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.99
Reduced primary intensity at cavity $e^{-(\mu_{ac} + \mu_{ak}) \frac{R_{10}}{2}}$	0.93	0.94	0.95	0.96	0.96	0.95	0.96	0.96	0.96	0.97
Sec. Absorp. $\mu_2 \frac{R_{10}}{2}$ (from table 5 line 3)	25	12.5	8.3	6.3	5.0	4.1	3.5	3.1	2.7	2.5
$-e^{-\mu_2 \frac{R_{10}}{2}}$	0	0	0	0	0.001	0.017	0.03	0.05	0.07	0.08
$e^{-(\mu_{ac} + \mu_{ak}) \frac{R_{10}}{2}} - e^{-\mu_2 \frac{R_{10}}{2}}$	0.93	0.94	0.95	0.96	0.96	0.93	0.93	0.91	0.89	0.89
$(\mu_{ac} + \mu_{ak})/\mu_2$ units 10^{-2}	0.30	0.49	0.65	0.78	0.93	0.98	1.13	1.19	1.29	1.33
$\frac{I_2}{I_{01}} = \frac{\mu_{ac} + \mu_{ak}}{\mu_2} (e^{-\mu_1 \frac{R_{10}}{2}} - e^{-\mu_2 \frac{R_{10}}{2}})$	0.279	0.460	0.616	0.750	0.890	0.910	1.05	1.08	1.15	1.18
$45/(\rho(E))^2 e 10^{-19}$ units	80.5	75.0	73.5	71.9	72	72	72	72	72	72
Air wall response $\frac{\text{Coul}}{\text{cm-photon}}$ 10^{-19} units	1.70	2.92	3.90	4.90	5.5	6.2	7.0	7.7	8.5	9.2
Effic. at 2.5 g/cm^2 wall	0.132	0.118	0.116	0.110	0.116	0.105	0.108	0.100	0.097	0.092
Normalized to 5 g/cm^2 wall	1.12	1.00	0.98	0.93	0.98	0.89	0.92	0.85	0.82	0.78

It will be noticed that the responses of all chambers are more variable than that of the 5 grams per square centimeter chamber, some exceeding its response and others falling below. The price for obtaining air response over the range is evidently having a smaller response at low energies. Small increases in wall thickness, however, will not make a chamber respond correctly over the entire range of energies, as the equilibrium one does. (See curve D for a rather large increase of thickness). (If the responses plotted in the Figure had been normalized to that of any thin walled chamber under bombardment by 1 MeV photons the relative positions of the curves would not be changed but the absolute values plotted would all have been much lower. One would think of the responses of all these chambers as being very much lower than they appear. The interest here is in higher energy response, however, and the 1 MeV response was computed only to tie the computations to familiar data).

In particular, for reactor radiation falling on the thin chambers a cutoff of response occurs somewhat beyond the photon energy corresponding to a wall thickness equal to the secondary electron range. Curve E shows that to reactór radiation the response of the 1/16" wall chamber is extremely low to photons above 3 MeV; similarly the response (not plotted) of the 1/8" wall chamber is about double that shown in curve E for photon radiation alone, with about the same degree of variability over the range of energies. Because of this variability, both wall thicknesses are too small for measuring dose near reactors.

The reason for the low response of the thin-wall chambers in reactor fluxes appears from Table 4. At lower energies the contributions of charge to the cavity from photons is more nearly the expected equilibrium response. But this response is chiefly from non-equilibrium photons materializing as electrons in the transition thickness available to the lower energy photons from the higher density, thin wall of the dosimeter. The walls are, however, too thin to sustain equilibrium response with higher energy reactor photons and the response falls.

In contrast, improvement of response in weapon flux over that from reactors at higher energies is due to the equilibrium contribution of the secondary, Compton and pair-process, electrons from external air. The net effect of the electrons is seen from comparing curves B and E for 1/16" wall response with and without secondary electrons. The responses differ greatly to the higher energy photons from 2 to 10 MeV. But in both kinds of fluxes, weapon and reactor, the dosimeters are energy dependent and consequently in error.

To remove energy dependence, the requirement that equilibrium be reached over the entire range of photon energies is evidently fundamental. It may, therefore, be necessary to ensure that primary-to-secondary equilibrium be reached to 10 MeV photon energies by going to the thick wall, 5 grams per square centimeter dosimeter. The attenuation of gamma intensity (line 5 of Table 5, for example) is nearly the same at all energies in such a dosimeter. At 2.5 grams per square centimeter wall thickness a less accurate response will be given at higher energy.

The effect of the thin wall in increasing the response when under bombardment by an equilibrium flux of electrons and photons is seen from curves A and B with C. In the limit when the chamber wall is infinitely thin the response at the highest energy, 10 MeV, is the same as that of the chamber with 5 grams per square centimeter wall which is in equilibrium under 10 MeV photons. Understanding of this result comes from Table 4 giving the component efficiencies from electrons and photons which make up the total efficiency. The efficiencies on photons progressively decrease going toward higher energies, while the efficiencies on electrons from the absorber-radiator increase with both thin walled chambers.

To summarize: The capability of personnel dosimeters to respond to gamma radiation dose from weapons or reactors has been studied. The conclusion is that conventional thin walled dosimeters will be relatively insensitive to higher energy γ radiation.

It has been shown here, however, that dose from either source can be registered in a thick-walled chamber, i.e., one thick enough to be in primary-to-secondary radiation equilibrium under the highest energy photons bombarding the dosimeter. In such a chamber the response at all energies is proportional, within acceptable error, to that of an ideal air wall chamber.

APPENDIX

ESTIMATION OF THE SECONDARY ABSORPTION COEFFICIENT FOR FAST ELECTRONS IN AIR AND AIR-EQUIVALENT CHAMBER WALLS

Because of the effect of scattering in traversing a medium,absorption coefficients have not been tabulated. It is nevertheless desirable to estimate the apparent absorption in thin and thick walls.

Data taken by Lenard reported in (4) by Andrade, show a linear decrease of transmission of fast electrons with absorber thickness over a considerable range to more than 2 grams per square centimeter of aluminum for about 3 MeV electrons. On the other hand, data by Marshall and Ward reproduced in (5) by Segre show an approximately linear decrease in transmission of electrons of 1.6 MeV after a thickness of 0.2 grams per square centimeter. These two transmission curves are not quite compatible. With still higher energy electrons than either of those reported on, it appears that at least a considerable region of linearity of transmission should occur, and removal of electrons could be computed on this basis.

For the purpose here, however, an exponential form for transmission has been assumed, and coefficients estimated which give a maximum of secondary intensity at about the range of the secondary particle.

On differentiating the secondary intensity, expression (V) with R replaced by the general thickness x, the maximum of secondary intensity is seen to occur at $x_{max} = \frac{\ln \frac{\mu_2}{\mu_1}}{\mu_2 - \mu_1}$. The ranges given in "The Atomic Nucleus" page 624 show that between energies 2 and 10 MeV the range is related to energy by R, grams/cm^2 = 0.5 E MeV, approximately. From these two relations the ranges and maximum secondary fluxes are as follows:

TABLE 7

Electron range compared to position at maximum secondary intensity in air wall dosimeters.

E, MeV	1	2	3	4	5	6	7	8	9	10
Range, Grams/cm^2	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
x_{max} grams/cm^2	0.58	1.05	1.52	1.91	2.30	2.67	3.00	3.4	3.8	4.1

The agreement between these two sets of figures indicates that the choice for μ_2 is not much in error; a similar calculation assuming the absorption coefficient to be 3/R, (instead of 5/R as in the above Table) shows much greater deviation over the entire energy range. If still closer agreement were desired than that given by $\mu_2 = 5/R$ a value of $\mu_2 = 4.5/R$ might give better agreement at the highest energies. At the approximation desired here such a refinement is unnecessary.

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The question of registering dose from weapon and reactor photons of 2 to 10 MeV energy has led to a study of the capability of conventional dosimeters and Geiger-Mueller tubes to respond accurately to these energies. Calculations of the response of thin and thick air-wall dosimeters have been made. The results are given as "efficiencies", or the ratio of the chamber response in charge per cubic centimeter in the dosimeter per incident photon fluence, to the same quantity in an ideal air wall chamber in electronic equilibrium. Stated in this way the results do not specifically refer to any type of chamber, but rather to interactions which result from normally incident photons. A very broad beam including scattered photons or an isotropic photon flux should give results approximately proportional to those computed.

The cases are analyzed of 1/16-in. and 1/8-in. air wall dosimeters under bombardment with these high energy photons, and also under bombardment with these photons plus the electron flux density coming from an air absorber of sufficient thickness to ensure primary to secondary radiation equilibrium. Finally dosimeters of two different wall thicknesses, 2.5 and 5 grams/cm^2, are studied, the latter of which can reach primary-to-secondary equilibrium under 10 MeV photons (and, of course, under all lower energies). The attenuation of the primary flux density is relatively small even at the larger thickness.

The results given in tables and a graph show that the thin wall dosimeters will give a distorted indication of dose at higher energies. The chamber with 5 grams per square centimeter wall responds in constant ratio to the response of the ideal air wall chamber for photons from 1 to 10 MeV and can therefore be used under all conditions for a register of dose.

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